Results on Higgs to fermions decays

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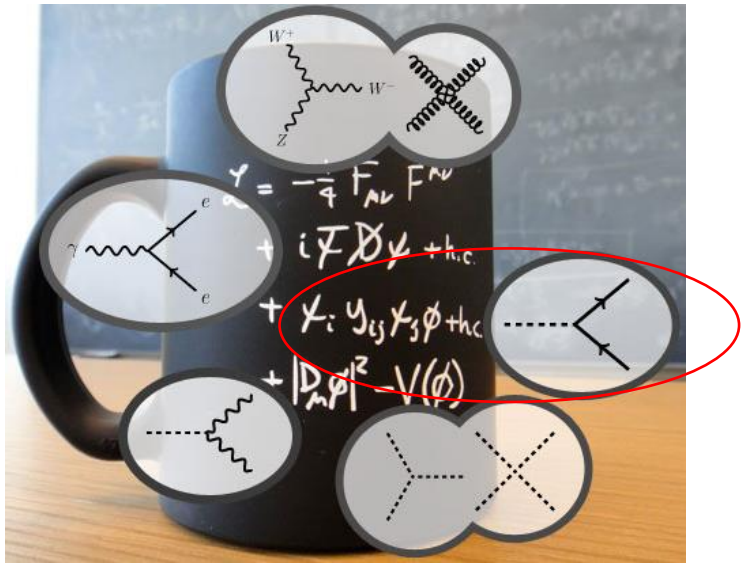
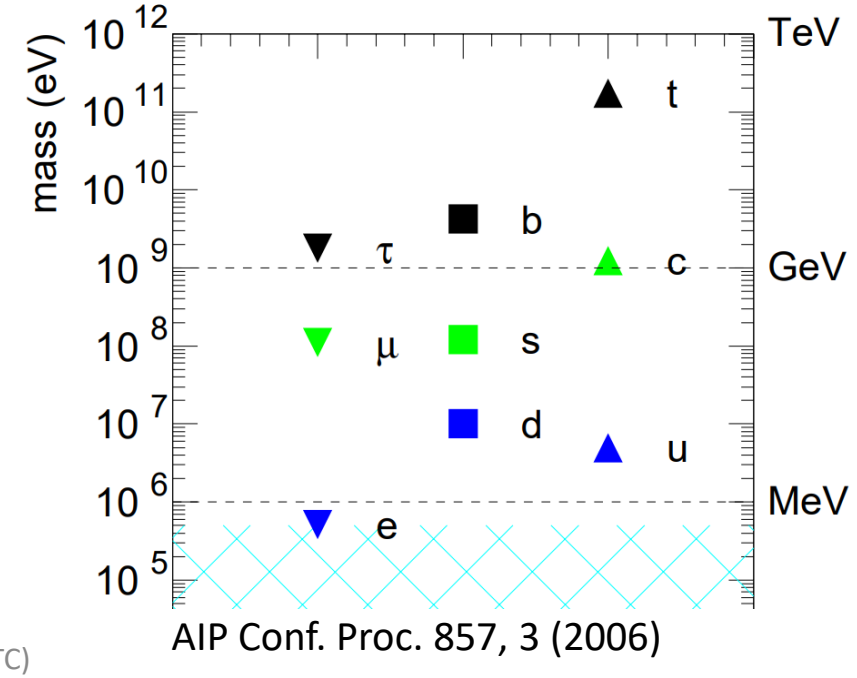
on behalf of the ATLAS and CMS collaborations

22nd, Nov. 2021, CKM 2021 @ University of Melbourne

Introduction

- In the Standard Model, Higgs-fermion Yukawa interaction generates mass for fermions
- Large scale in fermion masses is a mystery *(one of hierarchy problems in SM)*
- The Higgs sector of the Standard Model Lagrangian is the **origin of CKM matrix**, so measuring Yukawa coupling may hint on CKM matrix

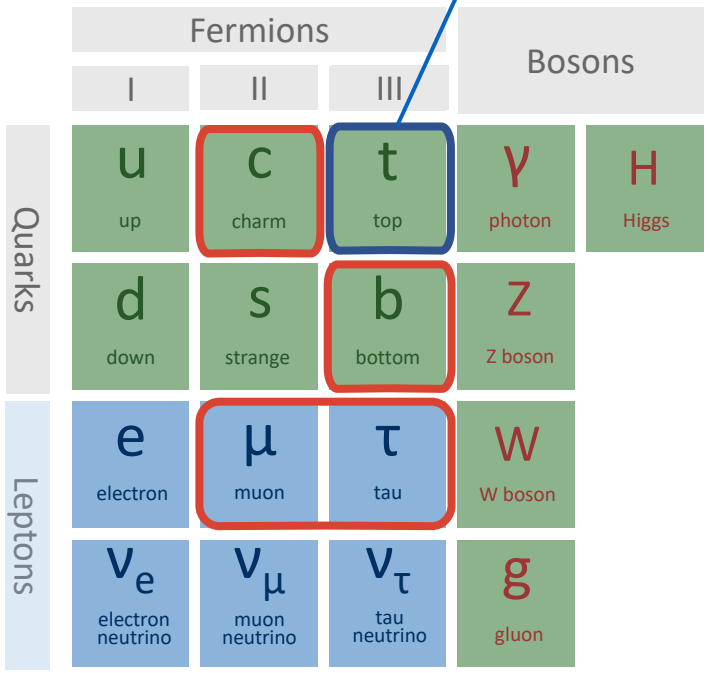




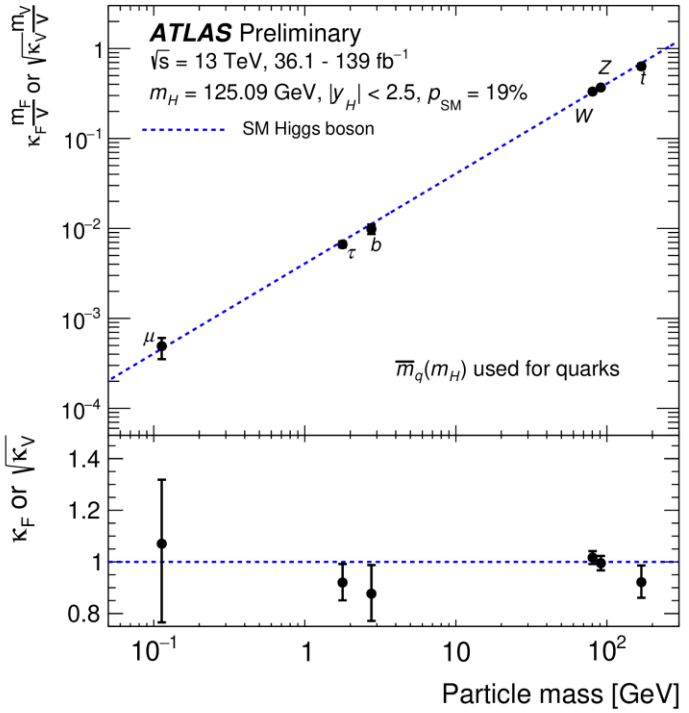
AIP Conf. Proc. 857, 3 (2006)

Overview

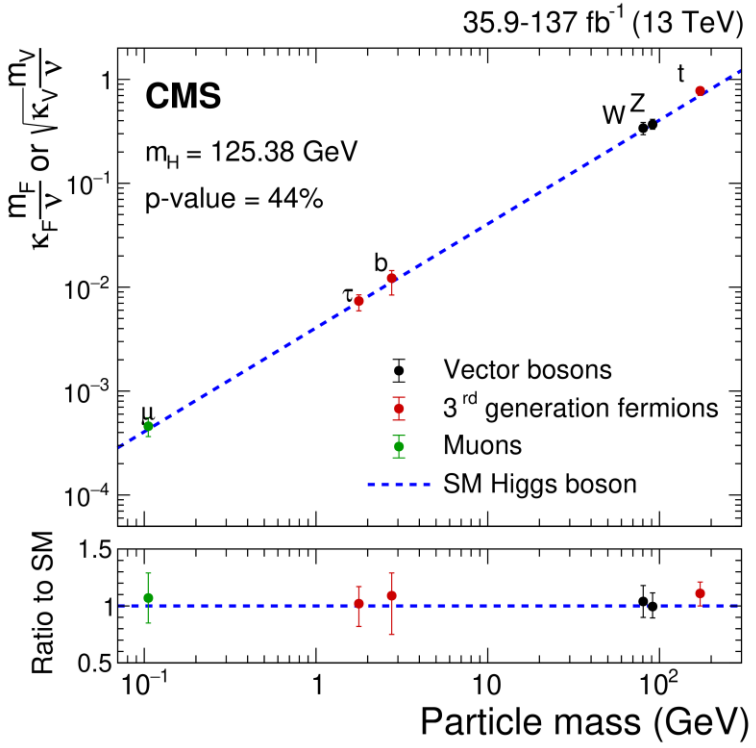
Dedicated talk later by Alexandra



ATLAS-CONF-2021-053

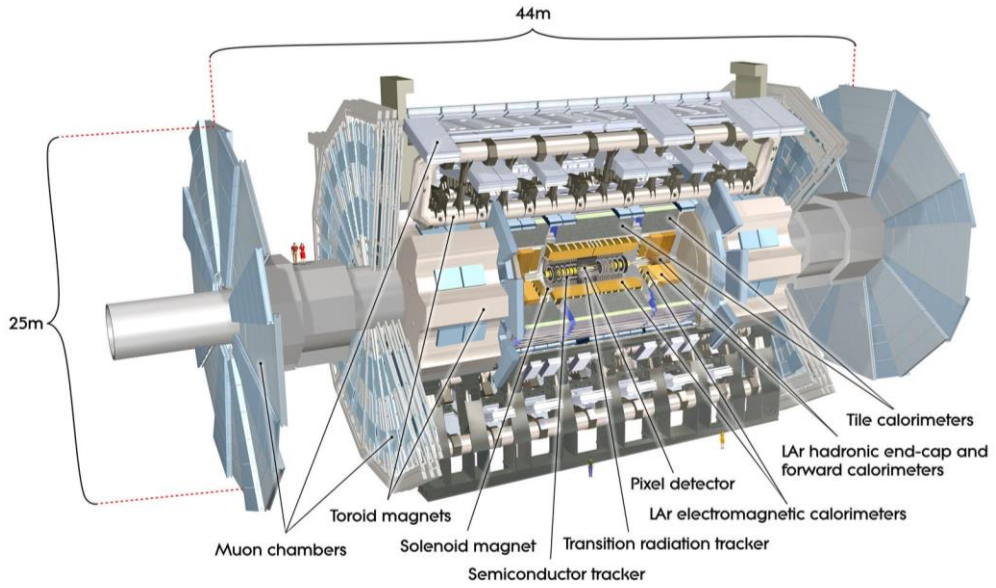


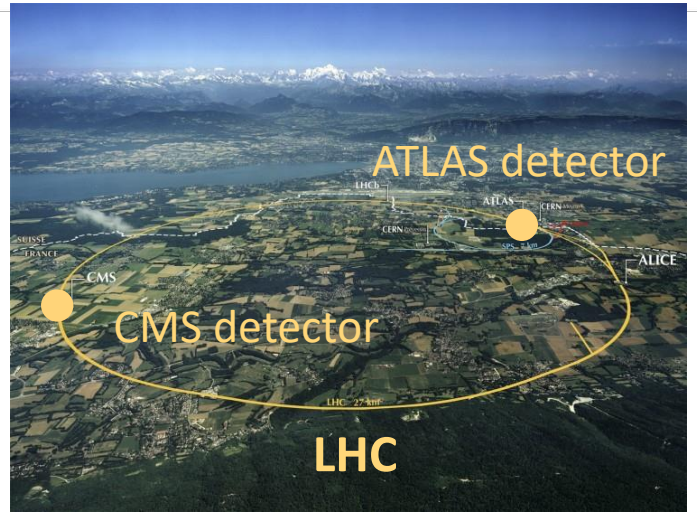
JHEP 01 (2021) 148



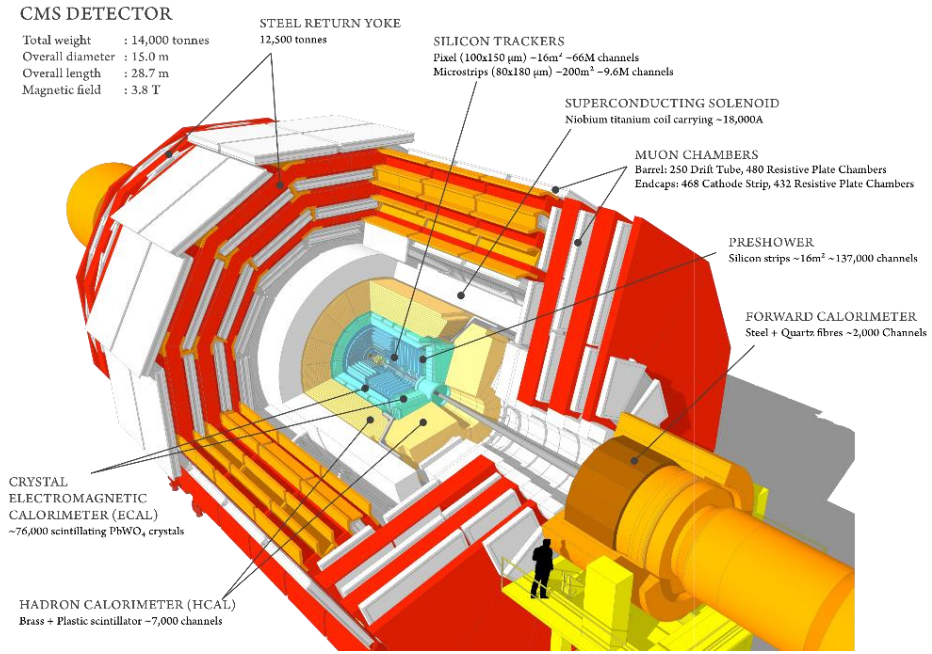
- All Higgs to third generation fermion couplings have been observed
- Second generation fermion Yukawa coupling searches progressed well, with evidence on H→μμ and H→cc upper limit set to O(10) level
- All measured results are compatible with SM predictions

Apparatus (ATLAS, CMS)

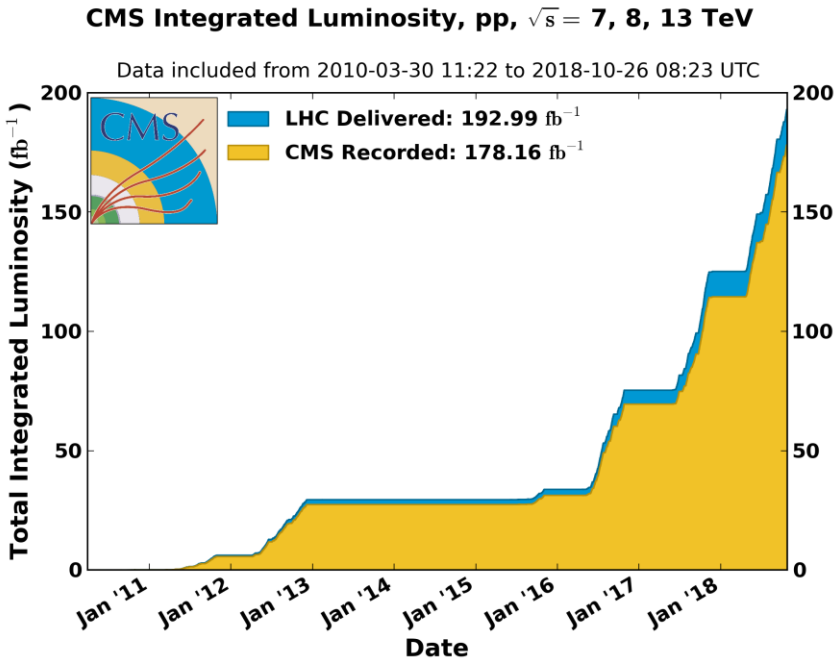




ATLAS (left) and CMS (bottom) are two multi-purpose detectors at the Large Hadron Collider which target Higgs/EW physics, and search for new physics



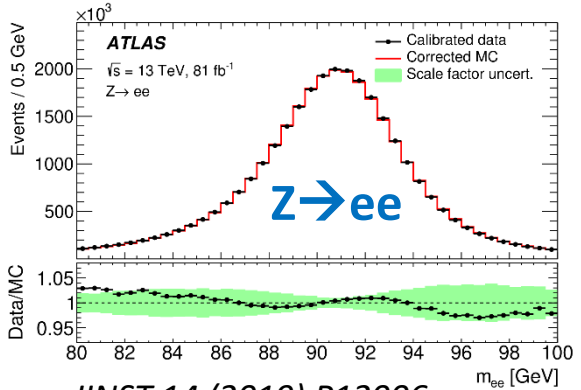
Data and Performance



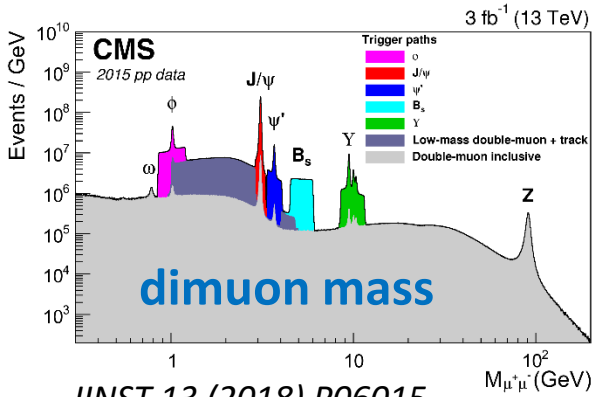
Data taking: Tremendous efforts from LHC, detector teams to make the data collection smooth

Physics successes owing to precise understanding of e, μ, jets, E_T^{miss}, and tagging of heavy-flavor jets

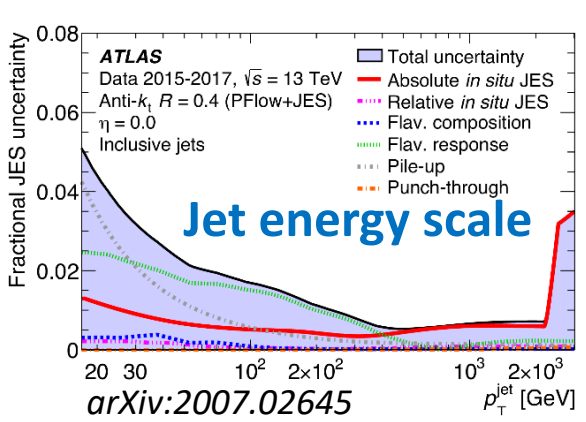
percent-level precision achieved in many



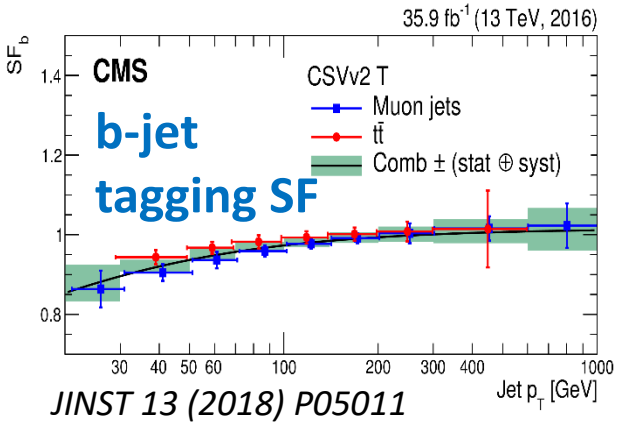
JINST 14 (2019) P12006



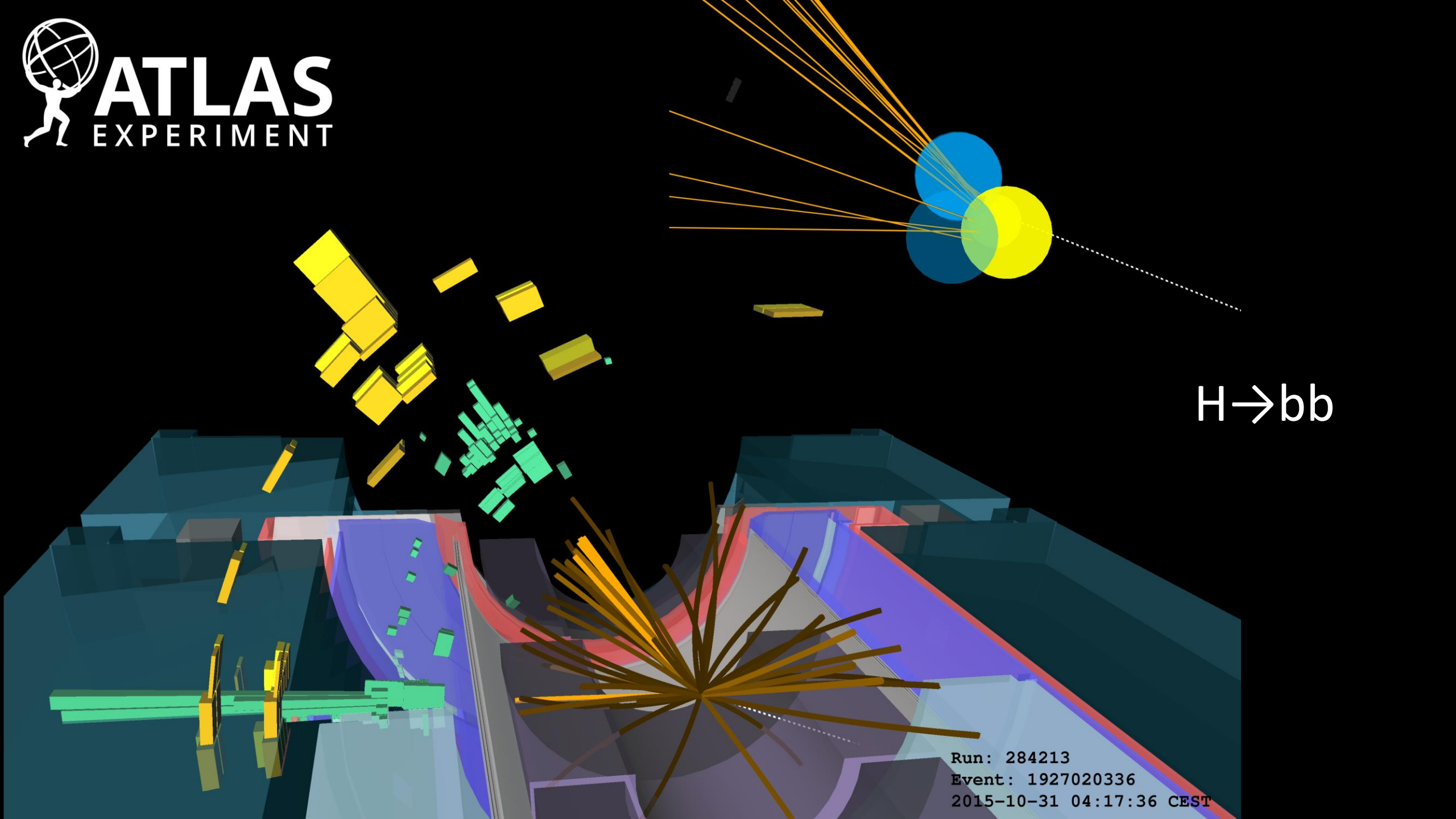
JINST 13 (2018) P06015



arXiv:2007.02645

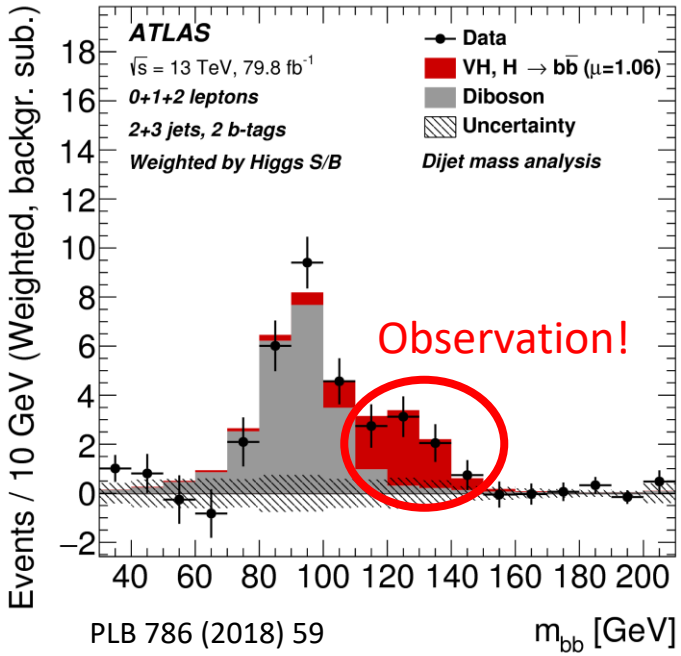


JINST 13 (2018) P05011

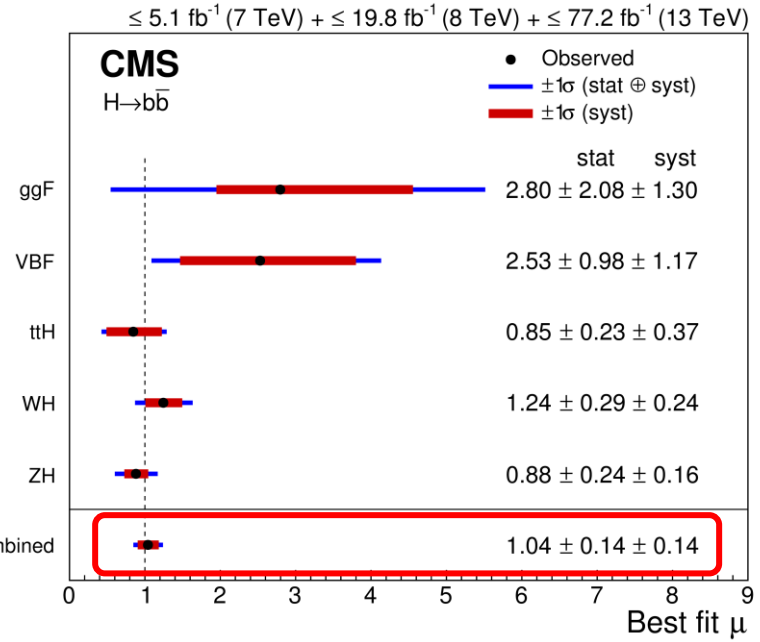

ATLAS
EXPERIMENT
H→bb
Run: 284213
Event: 1927020336
2015-10-31 04:17:36 CEST

H→bb

- Probe the Higgs coupling to third generation bottom type quark
- Observed mainly with VH production channel (pp→VH, H→bb)
  - ~5σ detection at both ATLAS and CMS in 2018
- B-jet tagging is one key factor



PLB 786 (2018) 59



PRL 121 (2018) 121801

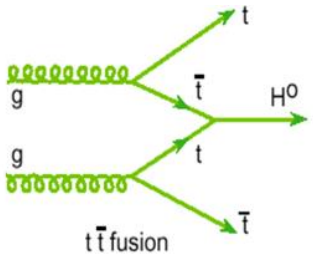
Achieved ~20% precision

Statistical uncertainty is about the same size as the systematic uncertainty

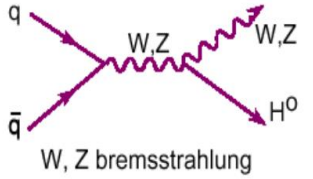
H→bb

EPJC 81, 178 (2021)
PRL 121, 121801 (2018)
EPJC 81, 537 (2021)
JHEP 03, 268 (2021)
PRL 120, 071802 (2018)
PRD 92, 032008 (2015)

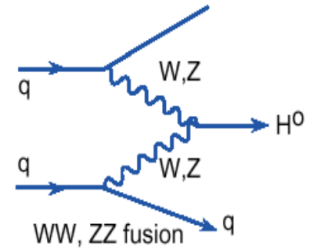
ttH
1%



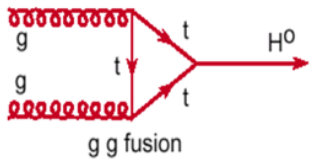
VH
4%



VBF
7%



ggF
88%



- Significance has been improved for VH resolved channel
- VH boosted channel has been explored and is progressing
- VBF channel has gained improvement and reached evidence

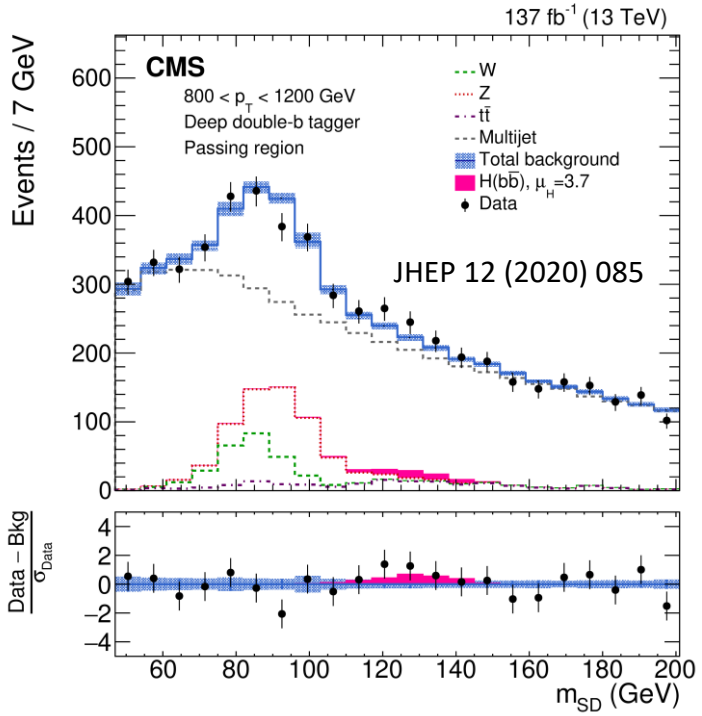
		ATLAS	CMS	
VH	resolved	6.7σ New!	4.8σ	7 TeV+8 TeV+41.3 fb^{-1} 13 TeV
	boosted	2.1σ New!	-	
VBF	-	2.9σ New!	2.2σ	19.8 fb^{-1} and 18.3 fb^{-1} 8 TeV
ggF	boosted	-	1.5σ	35.9 fb^{-1} 13 TeV
combined	-	-	5.6σ	7 TeV+8 TeV+41.3 fb^{-1} 13 TeV

*: 139 fb^{-1} 13 TeV

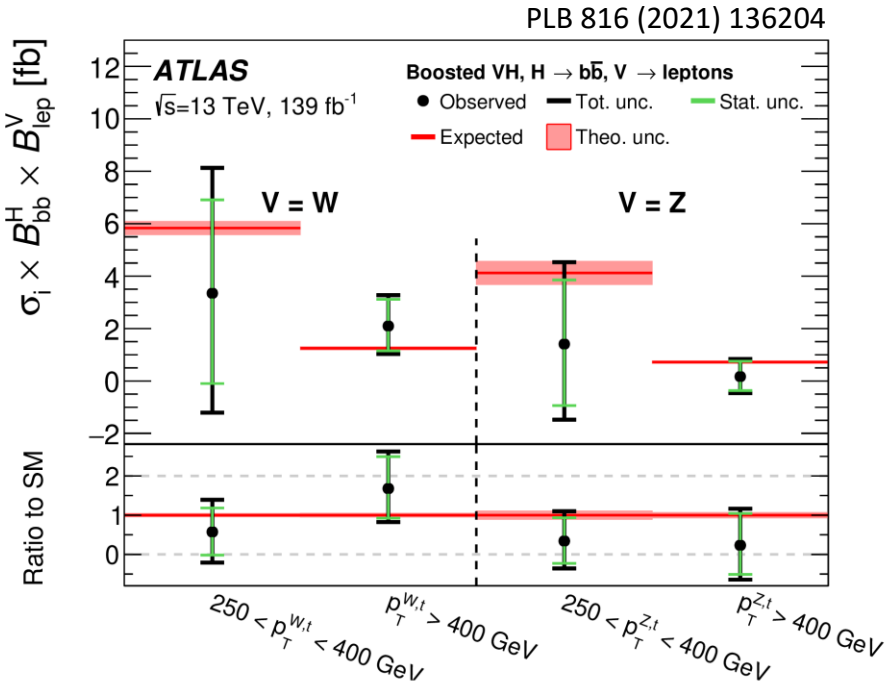
Highlights: H→bb boosted

- "Boosted" bb pairs → merged large-R jets *new physics sensitivity!*

ggF channel (*)



VH channel



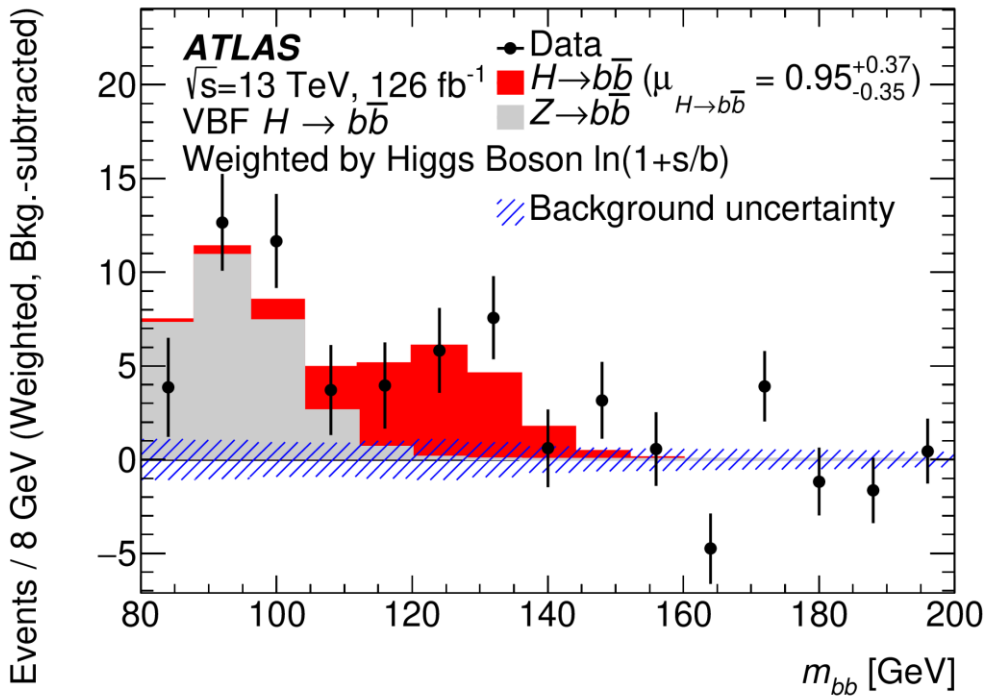
- Search H→bb out of enormous backgrounds
- Probe H→bb at TeV scale

Differential measurement in pT bins shows good agreement with SM

(*) ATLAS also has one boosted ggF result underway

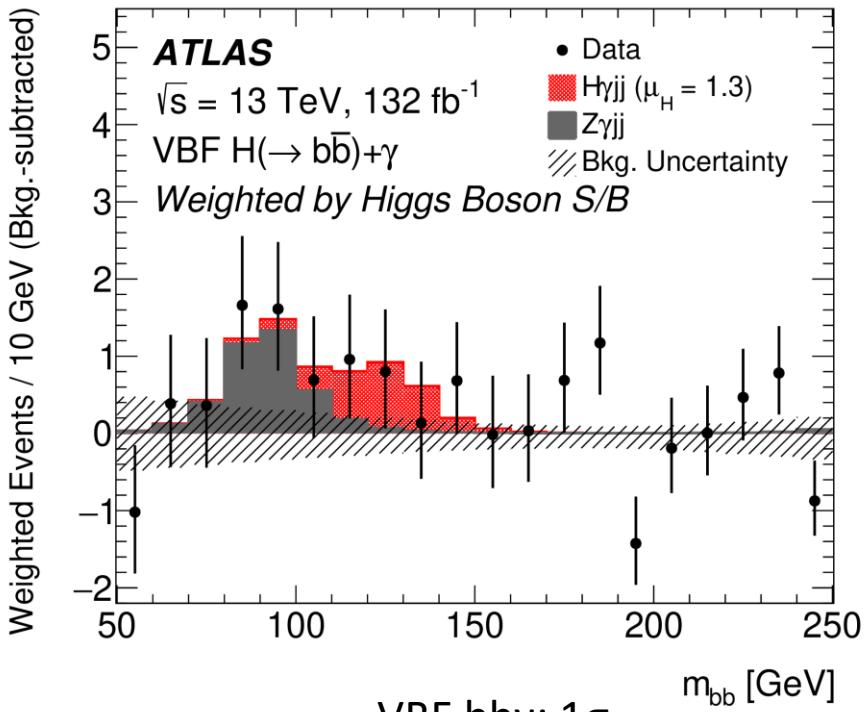
Highlights: Probing VBF production channel

EPJC 81 (2021) 537



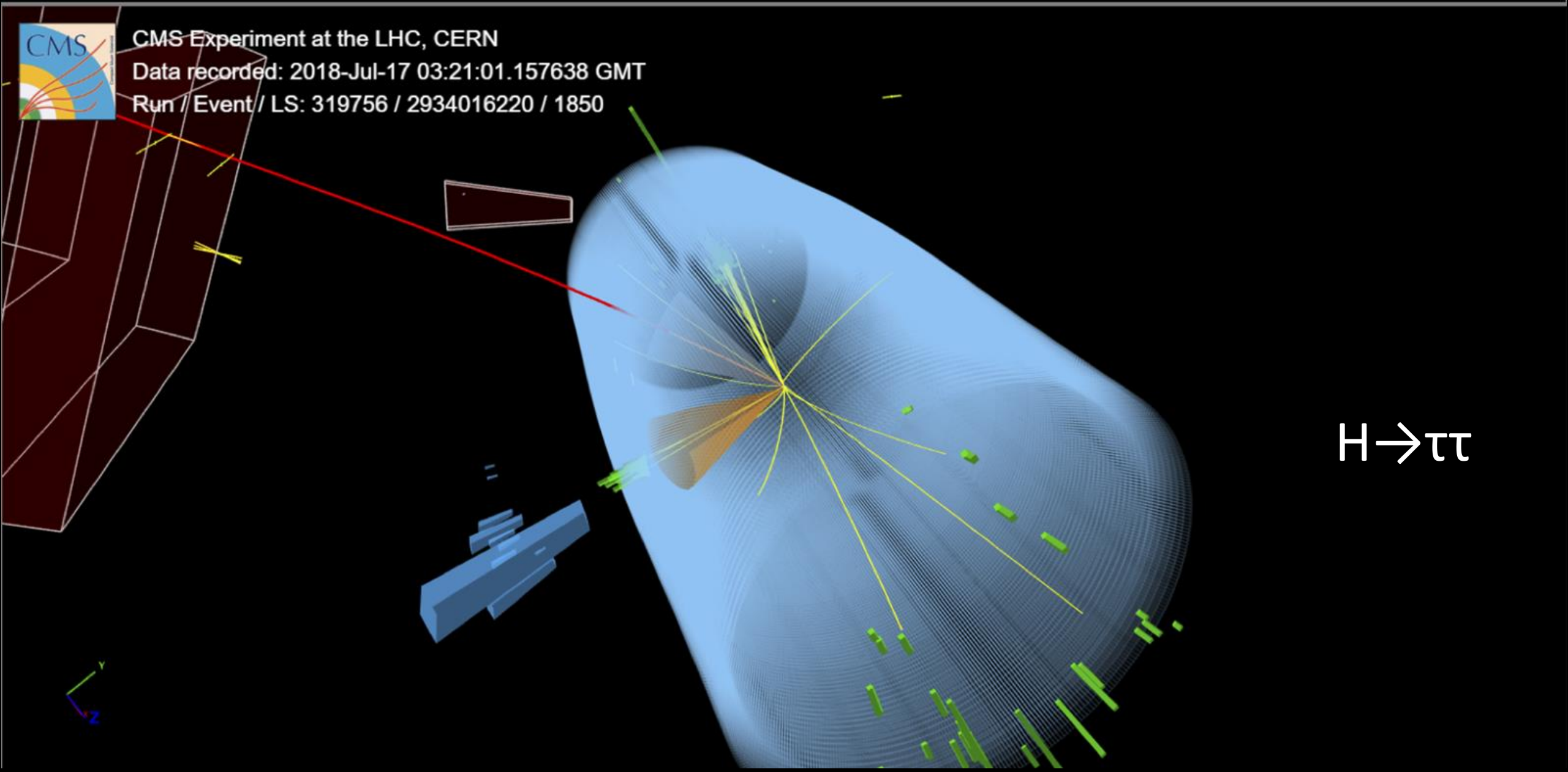
VBF: 2.9σ significance

JHEP 03 (2021) 268



VBF bbγ: 1σ

First search for (H→bb)+γ utilizing photon to largely suppress multijet background


CMS Experiment at the LHC, CERN
Data recorded: 2018-Jul-17 03:21:01.157638 GMT
Run / Event / LS: 319756 / 2934016220 / 1850
H→ττ

H→ττ

ATLAS-CONF-2021-044
PLB 779, 283 (2018)
JHEP 06 (2019) 093

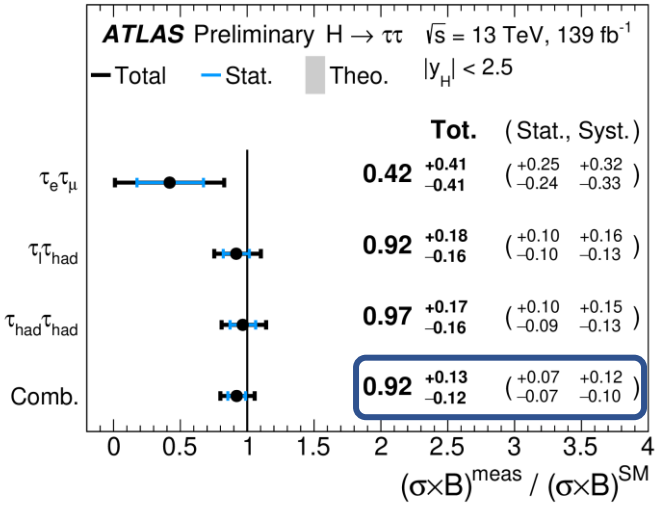
- Probe the Higgs coupling to third generation lepton – tau
- First observed in ATLAS+CMS combination with Run 1 data
- τ lepton need to be identified properly
  - electron/muon for leptonic decay
  - jet tagging/ML for hadronic decay

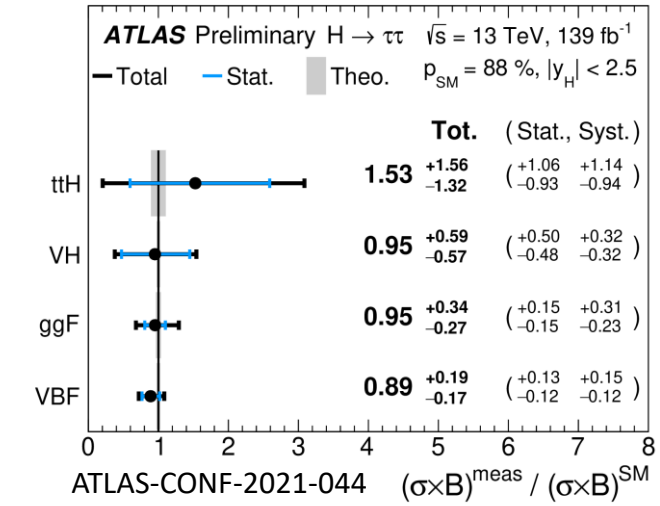
	ATLAS 139 fb^{-1} 13TeV	CMS 36 fb^{-1} 13TeV
VH	~50%	~100%
VBF	20%	30%
ggF	30%	90%
Combined	**10%**	**25%**

H→ττ cross section measurement precision

H→ττ

- Detailed measurements have been performed

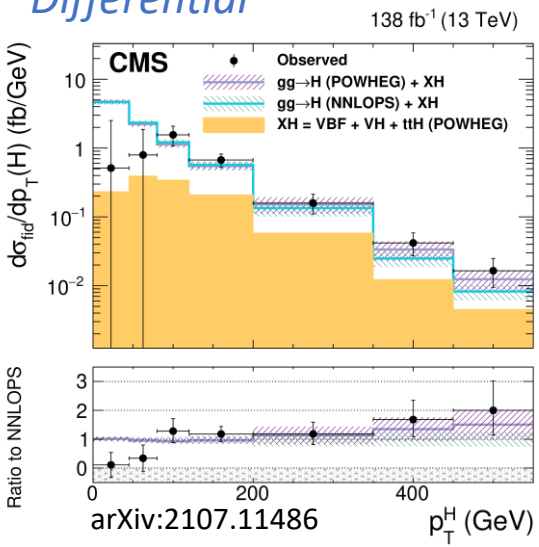




ATLAS-CONF-2021-044

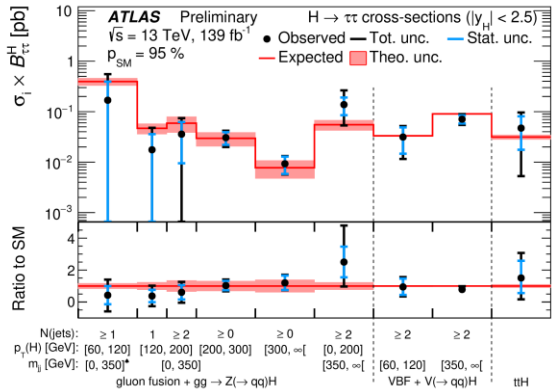
Close to 10% σ precision

Differential



Differential measurement result is compatible with SM to NNLO

STXS



Compatible with SM in all STXS bins

ATLAS-CONF-2021-044

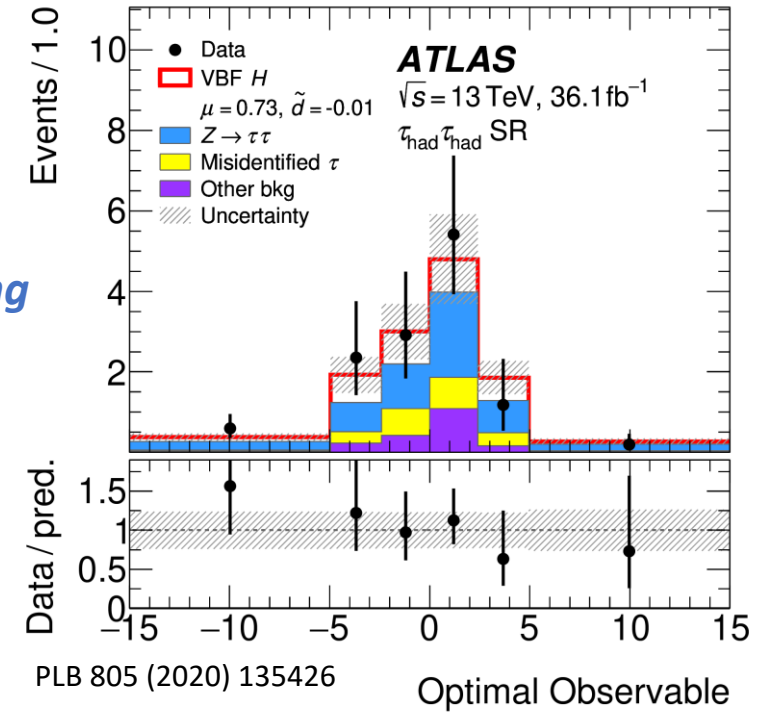
Highlight on study of CP structures

new physics possibility

- Hττ channel is one of optimal channels for **CP studies** in pp collisions

CP even-odd mixing

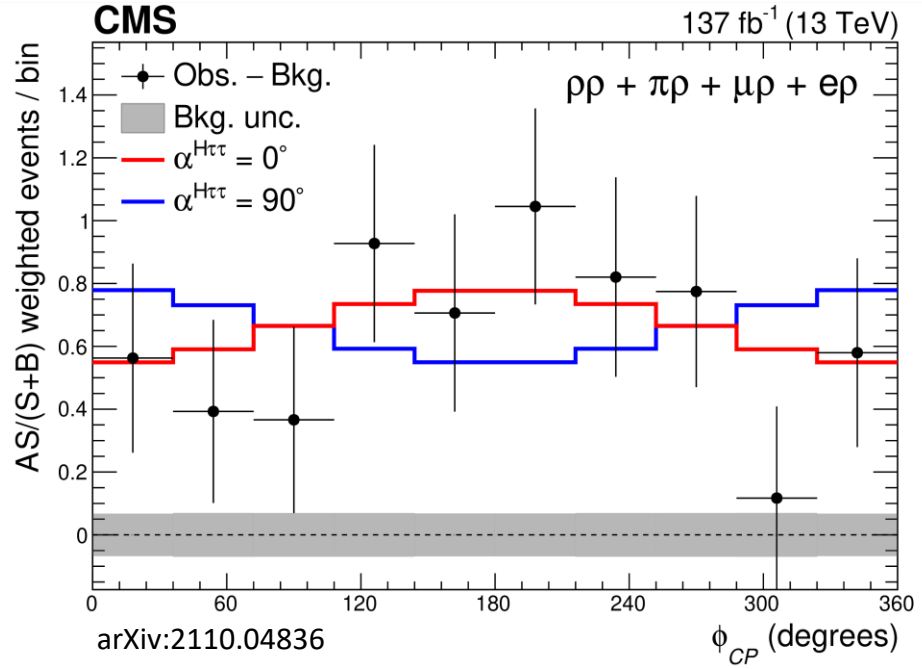
VBF events with CP-odd sensitive matrix-element variable



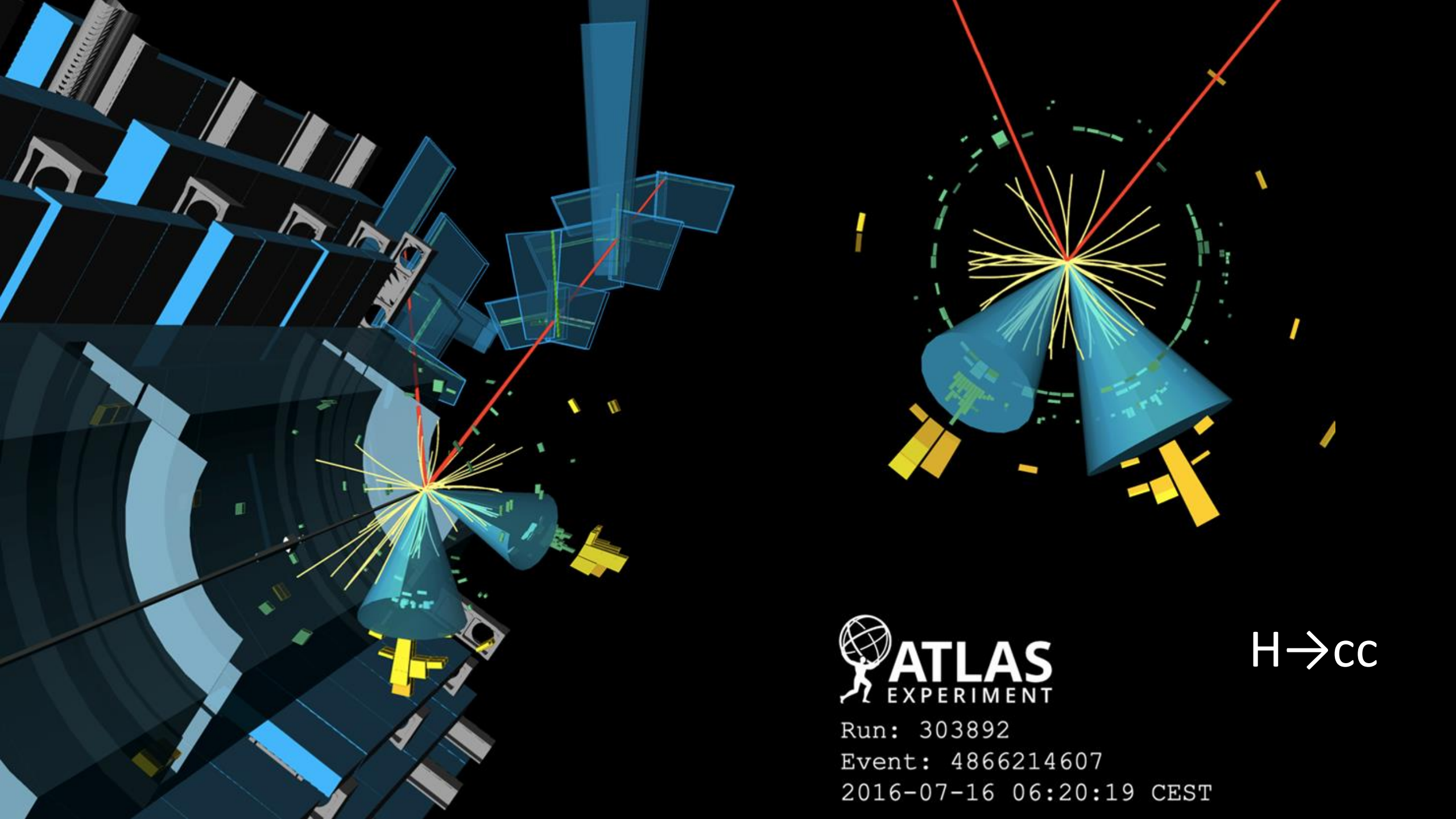
PLB 805 (2020) 135426

EFT CP-odd parameter
[−0.090, 0.035] at 68% CL
[−0.035, 0.033] expected

Inclusive events looking at τ decay planes with Machine learning



Odd-even Mixing angle
constrained to -1+/-19° at 68% CL
0+/-21° expected

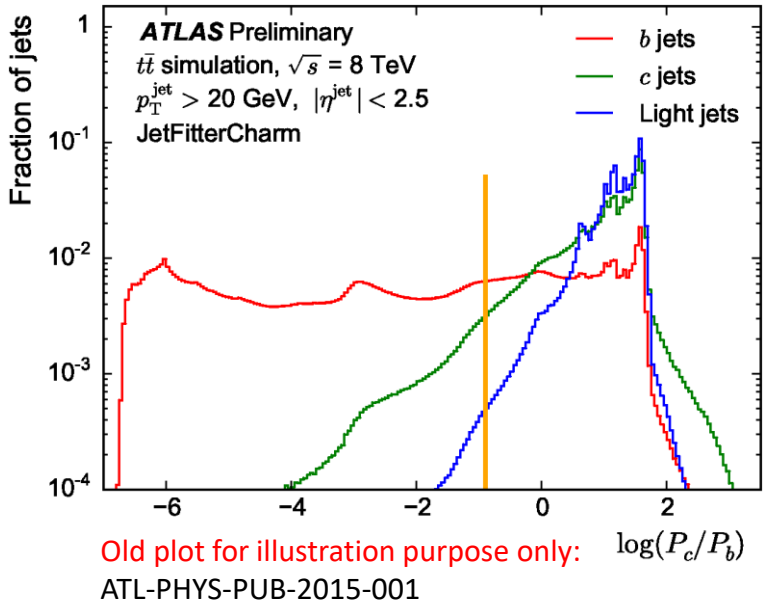

ATLAS
EXPERIMENT
Run: 303892
Event: 4866214607
2016-07-16 06:20:19 CEST
H→cc

H→cc

- Probe the Higgs coupling to second generation up type quark – charm
- Challenging part: charm tagging

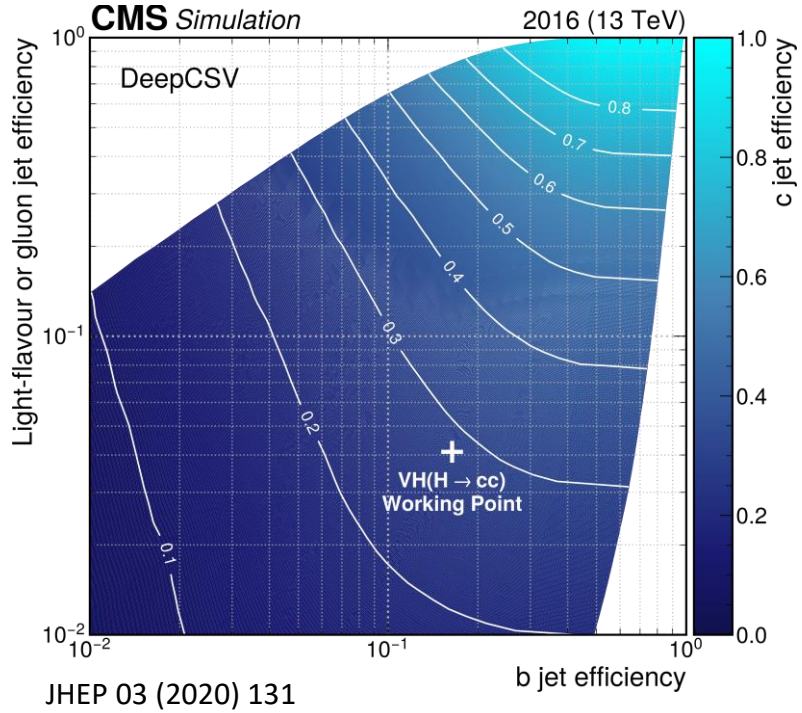
distinguish
- light/gluon jet
- charm jet
- bottom jet

Features:
- impact parameters
- secondary vertices
- topology
- …



Old plot for illustration purpose only:
ATL-PHYS-PUB-2015-001

Machine Learning



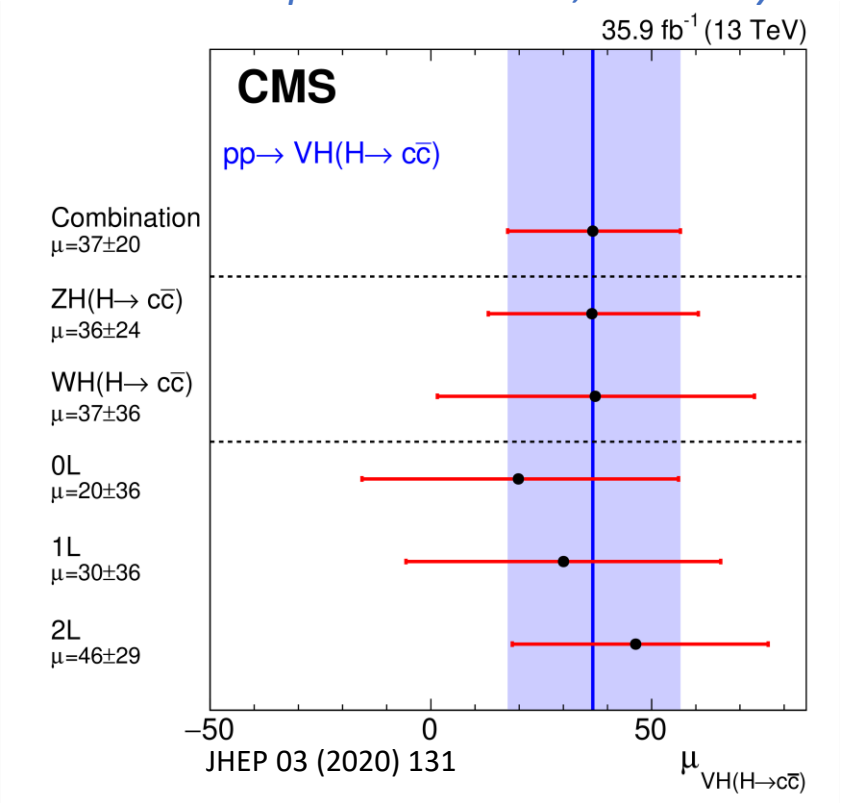
JHEP 03 (2020) 131

Working point achievable:
c eff: 20-40%, b rejection: ~10,
light rejection: ~50

H→cc

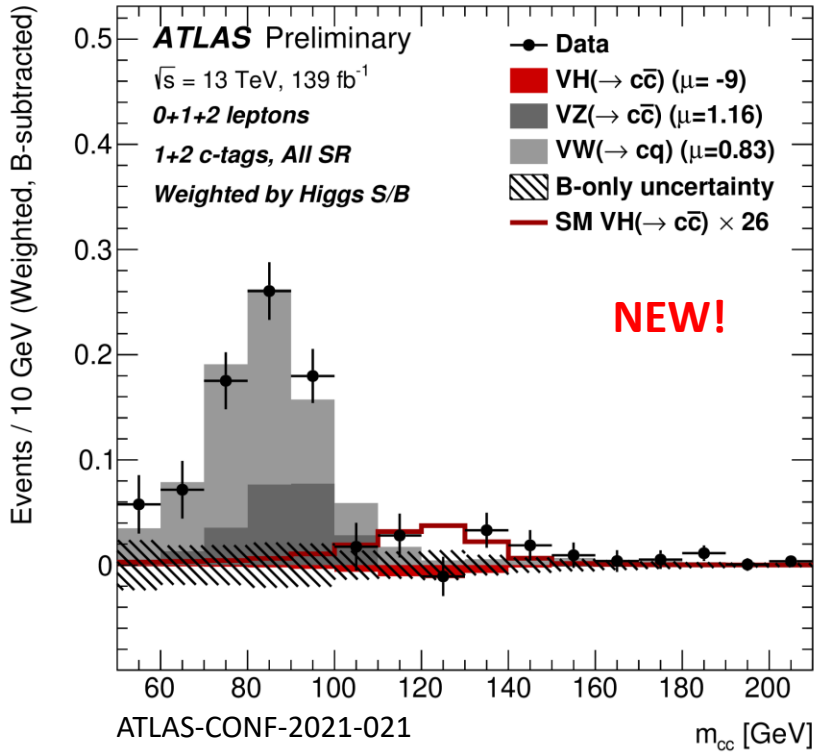
- VH production channel is the main channel explored so far

CMS: partial dataset, ML analysis



Upper limit on μ is 70 at 95% CL

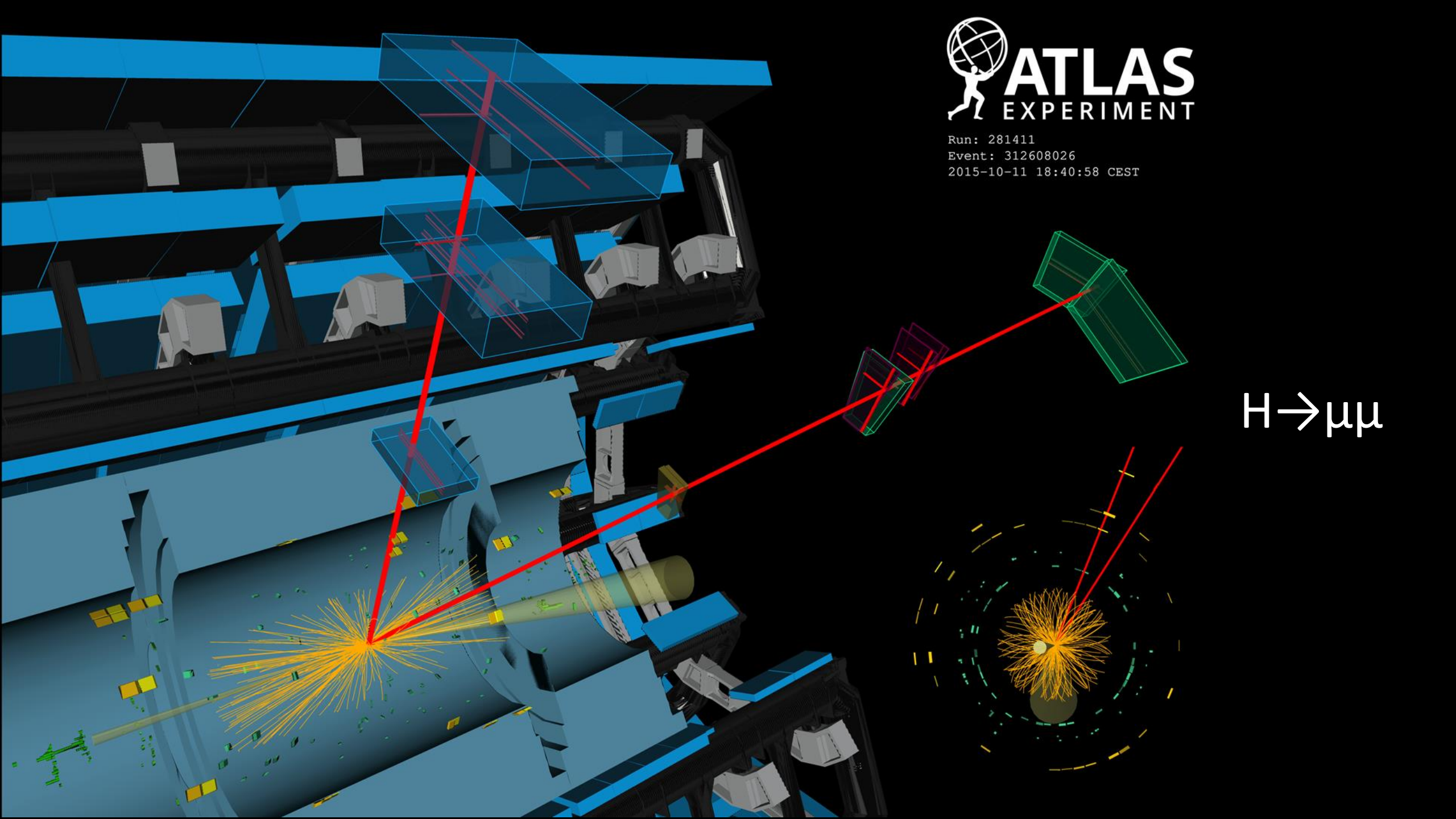
ATLAS: full dataset, cut-based analysis



Upper limit down to 26 at 95% CL

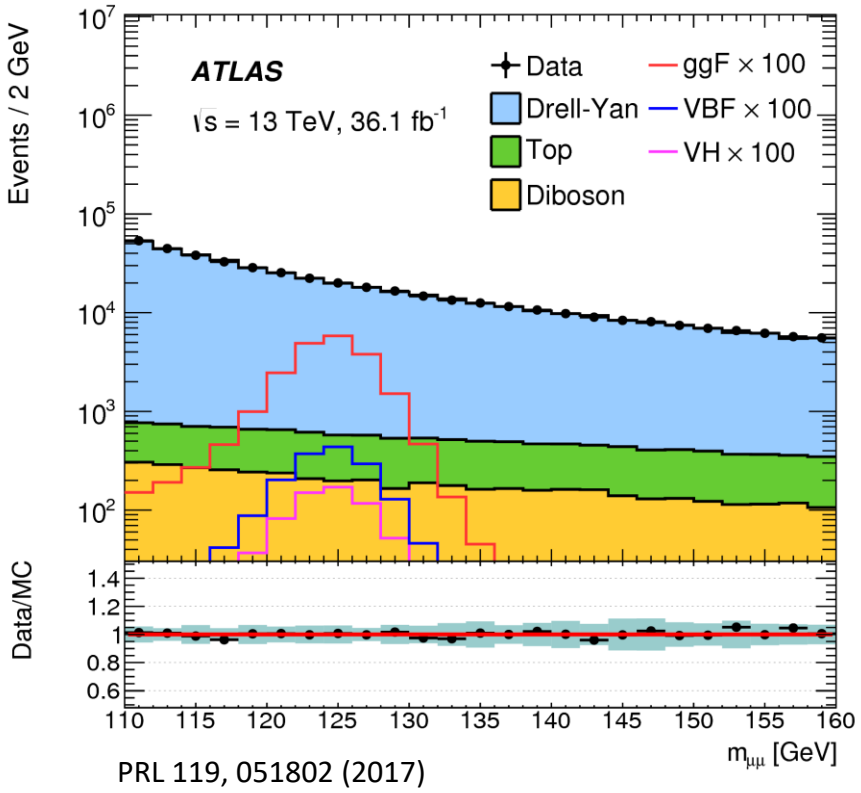
Diboson as validation with 3-5σ significance

Constraint on $|y_c/SM| < 8.5$


ATLAS
EXPERIMENT
Run: 281411
Event: 312608026
2015-10-11 18:40:58 CEST
H→μμ

H→μμ

- Probe the Higgs coupling to second generation lepton – muon
- Signature is clear, treatment for enormous backgrounds needed



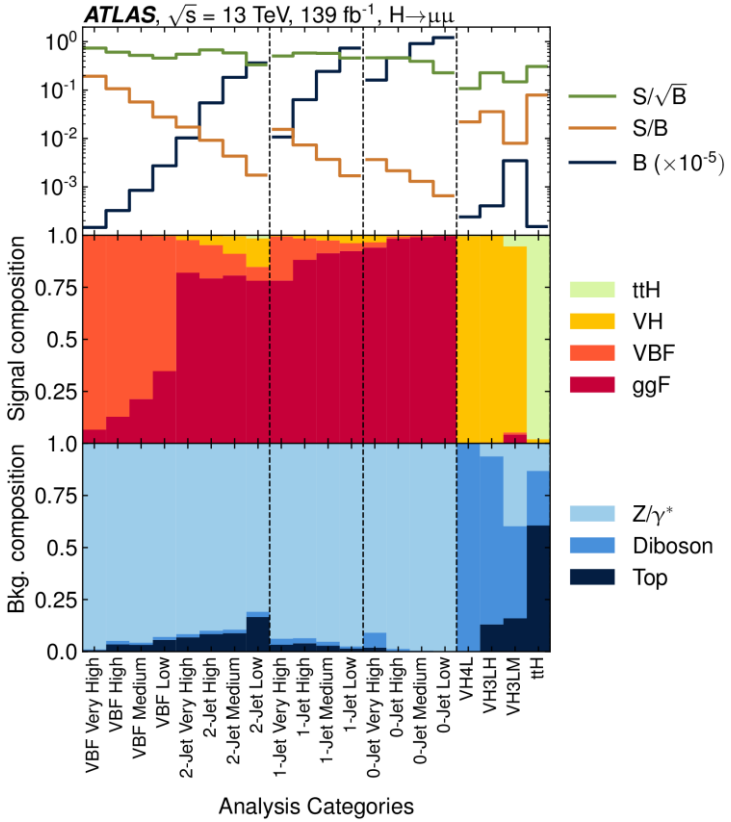
PRL 119, 051802 (2017)

To improve sensitivity:

- Signal categorization optimization
- Machine learning technique
- Ultrafast simulation allowing generating billions of events for background characterization

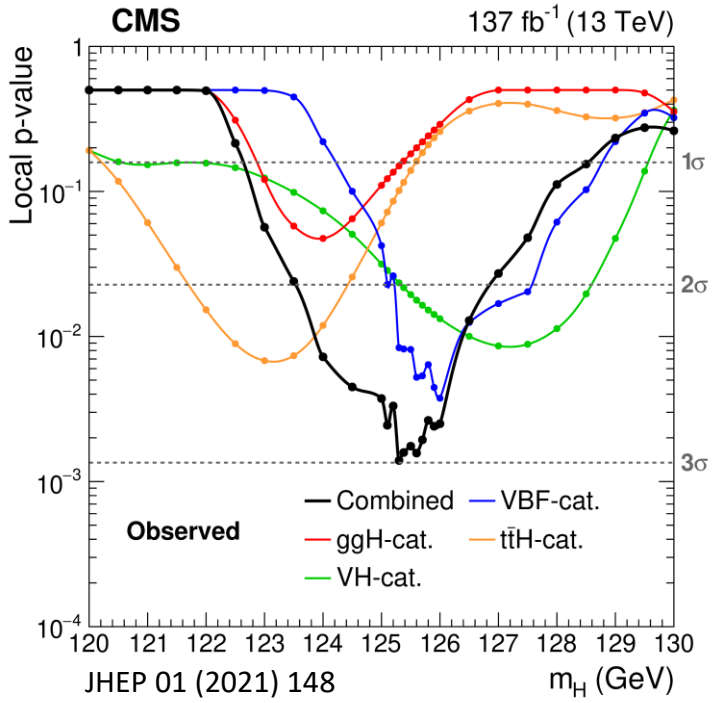
Highlight: **3σ evidence** for H→μμ

Signal categorization



PLB 812 (2021) 135980

CMS evidence

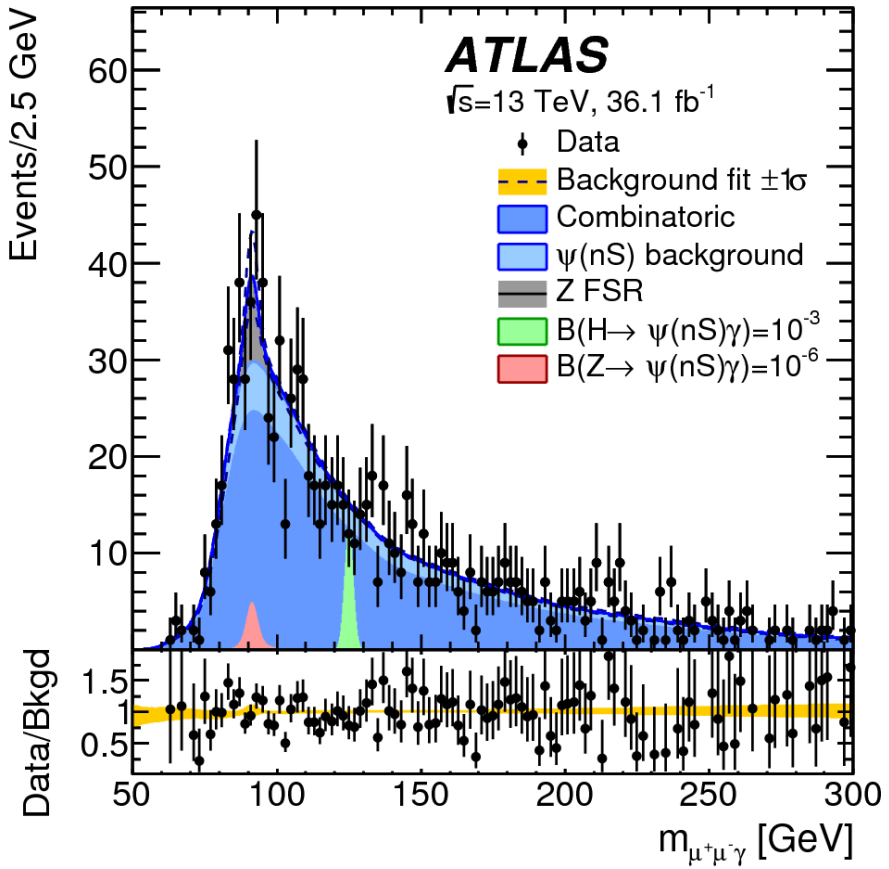


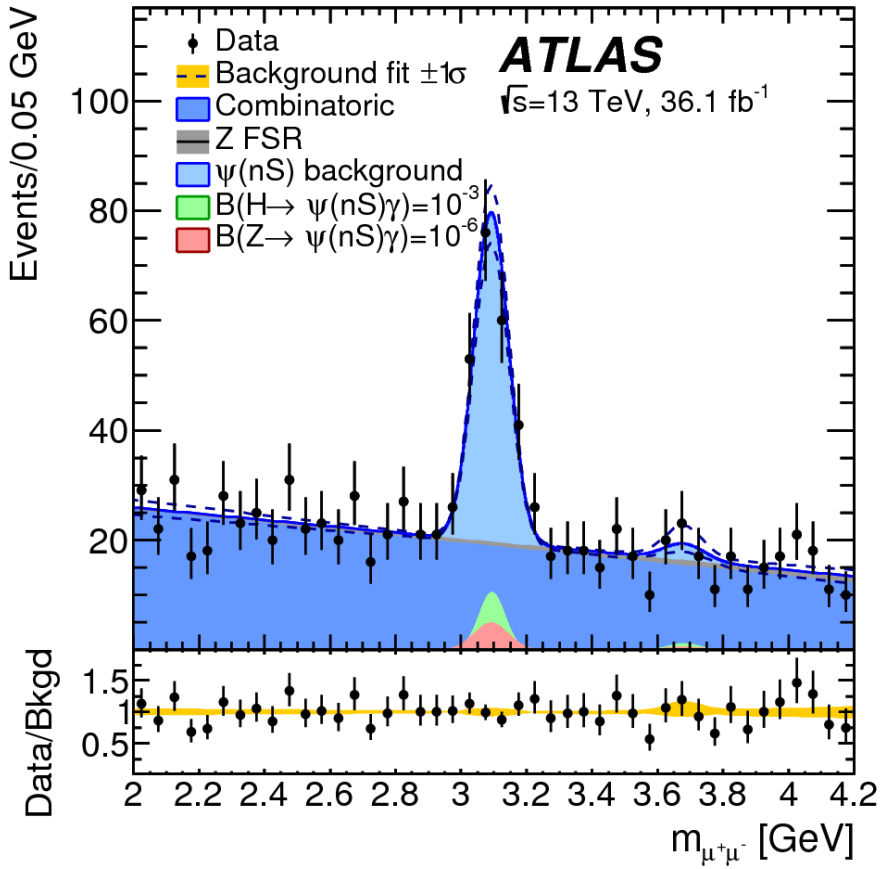
JHEP 01 (2021) 148

ATLAS achieved 2σ, CMS achieved 3σ. Combined, they can offer a strong 3σ evidence

Rare Higgs decays

- Rare channels for bottom and charm: H→J/ψ, ψ(2s), ϒ(ns) + γ





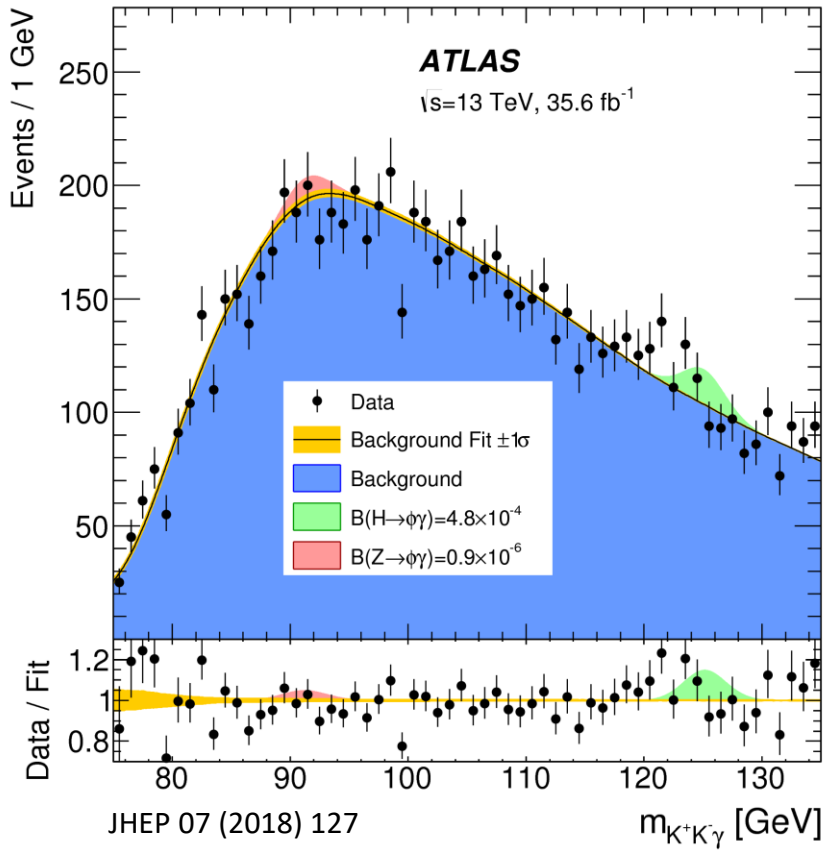
Current upper limit on branching ratios: ~ 10^{-3} – 10^{-4} (SM prediction ~ 10^{-6}) less sensitive than direct method so far

PLB 786 (2018) 134

H→ψ(nS)γ, ψ(nS)→μμ

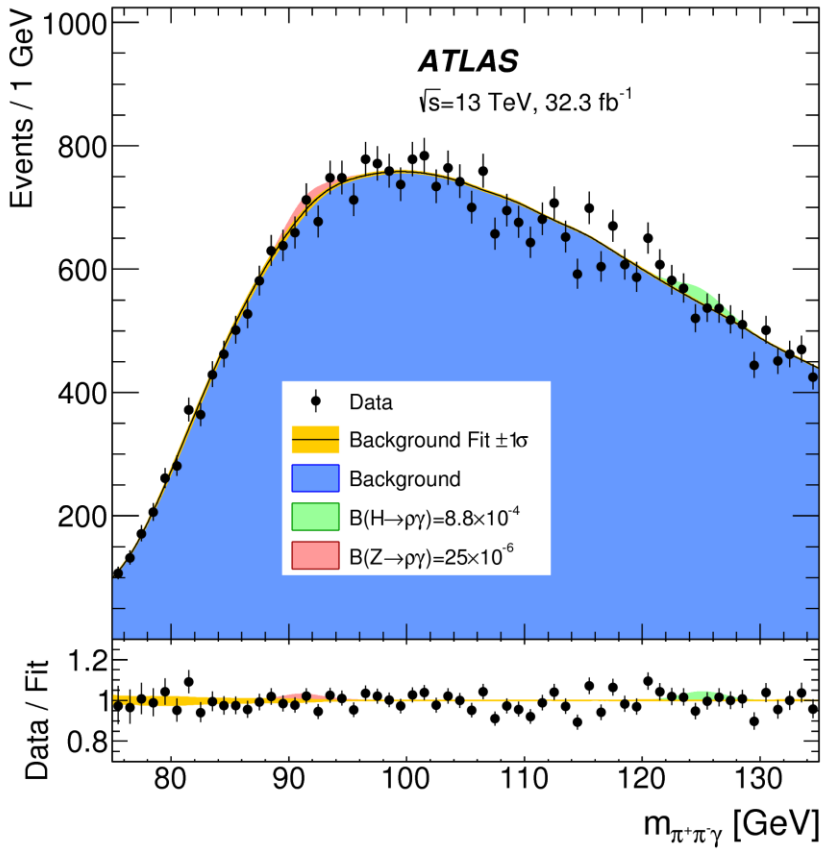
Rare Higgs decays

- Rare channels for strange: H→ρ, ϕ+γ



JHEP 07 (2018) 127

H→ ϕγ, ϕ→K^+K^-



H→ ργ, ρ→$\pi^+\pi^-$

Current upper limit on branching ratios:
~ 10^{-3} – 10^{-4}
while SM prediction for branching ratio is
~ 10^{-5} – 10^{-6}

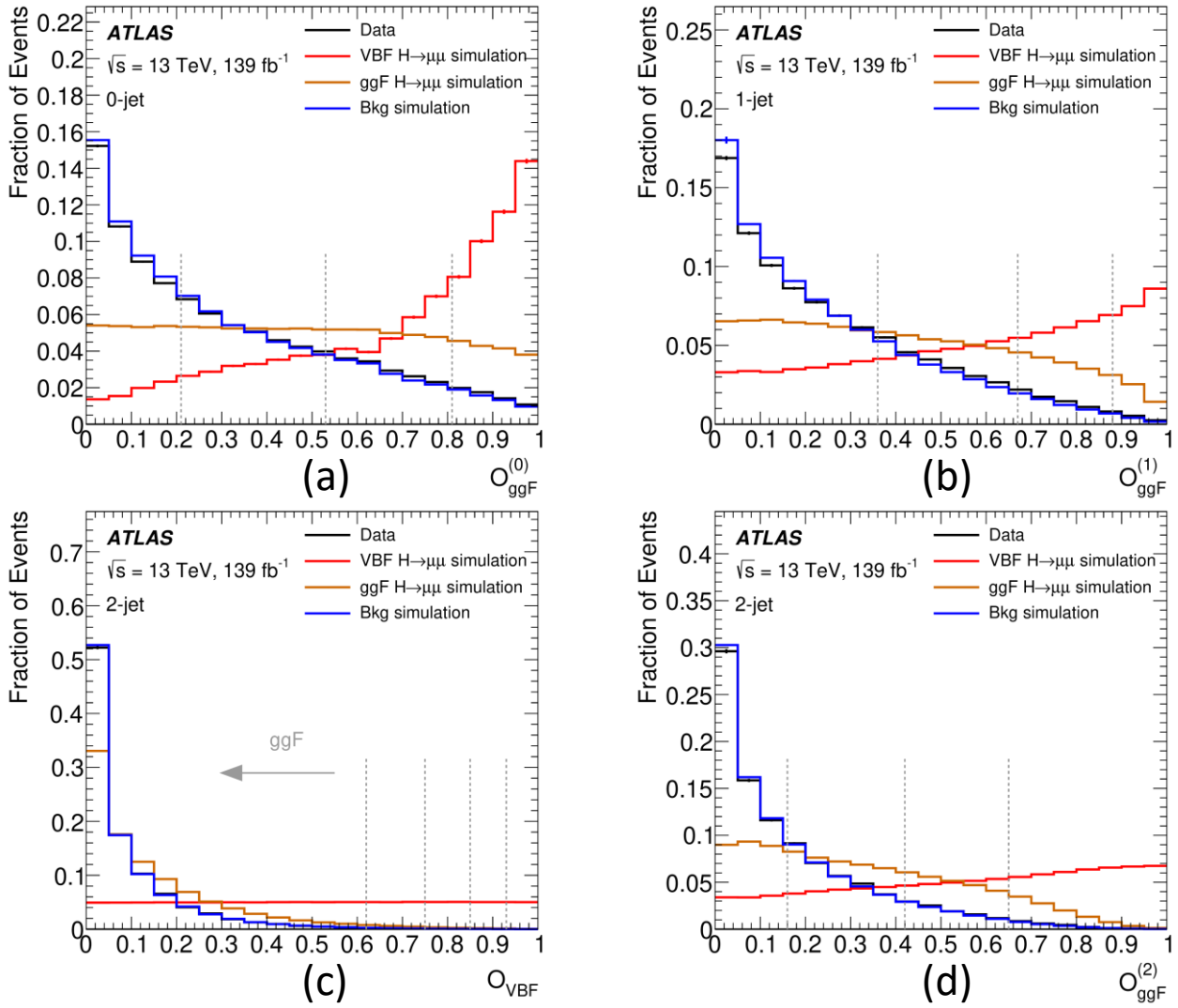
Summary

- Higgs couplings to 3rd-generation fermions are well established. All measurements are consistent with the Standard Model predictions
- Large branching fractions to b quarks make it possible to probe high-p^T Higgs production
- Search for **H→μμ** decays gained evidence. As for **H→cc**, the upper limit has gained significant improvement and has been set to **26 x** SM prediction
- Higgs decaying to very rare channels have been searched for. No obvious deviations were found
- The searches have been done with diversity to reach most optimal results for each generation
- More detailed probe underway and to be followed up with LHC Run-3, and with HL-LHC

Thanks for listening!

Backup

H→μμ categorizations



The multivariate ggF+VBF classifiers used in the analysis for (a) 0-jet events, (b) 1-jet events, (c)+(d) 2-jet events, all restricted to the region $m_{\mu\mu}$ = 120–130 GeV

charm-tagging taggers

EPJC 79 (2019) 970

JHEP 08 (2018) 89

- Input variables used by the MV2 and the DL1 algorithms:
  - IP2D/IP3D
    - $\log(P_b/P_{\text{light}})$
    - $\log(P_b/P_c)$
    - $\log(P_c/P_{\text{light}})$
  - SV1
  - JetFitter
  - JetFitter c-tagging